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E_6 leptoquarks and the solar neutrino problem

Esteban Roulet

NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510-0500

The possibility that non-conventional neutrino oscillations take place in the superstring inspired E_6 models is considered. In this context, the influence of leptoquark mediated interactions of the neutrinos with nucleons in the resonant flavor conversion is discussed. It is shown that this effect can be significant for $\nu_e - \nu_\tau$ oscillations if these neutrinos have the masses required in the ordinary MSW effect, and may lead to a solution of the solar neutrino problem even in the absence of vacuum mixings. On the other hand, this model cannot lead to a resonant behaviour in the sun if the neutrinos are massless.

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The most plausible explanation of the observed deficit of solar neutrinos is the resonant conversion in the sun of the ν_e to another neutrino flavor, i.e. the so-called Mikheyev-Smirnov-Wolfenstein (MSW) effect [1,2]. In a recent work [3], I analyzed the possible matter induced resonant enhancement of the neutrino oscillations caused by flavor changing ν interactions (FCI) rather than by the enhancement of a vacuum mixing. It was shown that strengths of the FCI of the order of $10^{-3} \div 10^{-1}$ G_F, with neutrino square mass differences $\Delta \equiv m_2^2 - m_1^2 \sim 10^{-8} \div 10^{-4}$ eV^2, can explain the observed deficit of solar neutrinos in a way very similar to the ordinary MSW effect but even in the absence of neutrino mixing in vacuum. The required ν properties were shown to be achievable in the minimal supersymmetric standard model in the presence of some R-parity violating couplings, for which $\nu_e - \nu_\tau$ oscillations can be induced consistently with the various phenomenological constraints. In ref. [4], the possibility of obtaining a resonant behaviour in the absence of neutrino masses by means of new flavor diagonal ν interactions (FDI) has been also considered and the general mechanism has been further analyzed in ref. [5].

Given the potential relevance of this scenario, it is interesting to search for other models where this mechanism may work. In particular, I will analyze the possibility of obtaining these new ν interactions in the superstring inspired E_6 models, that are one of the best motivated low-energy extensions of the standard model (SM). In this context, the new processes can be due to the interactions of neutrinos with nuclei mediated by leptoquarks.

In the superstring inspired E_6 models [6], the low energy gauge group usually includes an extra U(1) factor besides the SM group and each generation lies in a 27-dimensional representation of E_6, that contains the ordinary quarks $Q = (u, d)^T$, d^c, u^c, the leptons $L = (\nu, e)^T$, e^c and twelve new exotic states: a vector singlet quark D, D^c, a vector doublet of leptons E, E^c (whose scalar counterparts are the usual Higgs doublets) and two neutral singlets N and ν^c. In terms of these fields, the superpotential couplings contained in the 27^3 of E_6 are (omitting generation indices)

$$
\begin{aligned}
W = & \lambda_1 E Q u^c + \lambda_2 E^c L e^c + \lambda_3 E^c Q d^c + \lambda_4 E E^c N \\
& + \lambda_5 D D^c N + \lambda_6 E L \nu^c + (\lambda_7 D Q Q + \lambda_8 D^c u^c d^c) \, . \\
& + (\lambda_9 D e^c u^c + \lambda_{10} D^c L Q + \lambda_{11} D \nu^c d^c)
\end{aligned}
\tag{1}
$$

The first six terms are responsible of giving masses to the fermions and in particular the term proportional to λ_6 can give Dirac masses to the neutrinos. Instead, there are no Majorana mass terms for the ordinary neutrinos (no isospin triplets in the 27 representation) nor terms providing large Majorana masses for the neutral singlets, so that the seesaw mechanism can not be effective. Also, in contrast with the supersymmetric model with broken R parity, Majorana mass terms for the ordinary neutrinos are not generated radiatively, but instead some combinations of couplings may generate Dirac ν masses at one-loop ($\propto \lambda_{10}\lambda_{11}$) or two loops [7]. In order not to violate laboratory and cosmological bounds one should ensure that the contributions to the neutrino masses are small. Furthermore, to get the tiny masses required for the MSW effect ($10^{-4} \div 10^{-2}$ eV), the couplings should be even more suppressed. In these theories, the smallness of the neutrino masses can be more naturally understood if some discrete symmetries (or topological properties of the compactification manifold) imply the absence of some (or even all) of the Yukawa couplings generating the ν mass terms, and then only the couplings that are left need to be sufficiently small.

Considering now the remaining terms in eq.(1), it is clear that the couplings in both brackets cannot be all allowed simultaneously without inducing too fast proton decay, so that usually one of the brackets is eliminated invoking some symmetry. If the first one is allowed, the quark D has the quantum numbers of a diquark, while if the second one is allowed, D is a leptoquark, connecting a lepton with a quark. This last possibility is the one that will be analyzed in more detail since it could be relevant for the ν oscillations.

In particular, the coupling $\lambda_{ijk}D_i^c L_j Q_k$ ($\lambda_{10} \equiv \lambda$) induces the following effective interaction for the neutrinos with the down quarks, mediated by the scalar leptoquarks $\tilde{D}$

$$-\mathcal{L} = \sqrt{2}G_{ij}\bar{\nu}_{iL}\gamma_\mu\nu_{jL}\bar{d}\gamma^\mu(1-\gamma_5)d, \tag{2}$$

with

$$\sqrt{2}G_{ij} \equiv \frac{\lambda^*_{ki1}\lambda_{kj1}}{4m^2_{\tilde{D}_k}}. \tag{3}$$

In the presence of these interactions, the ν oscillations are governed by the equation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\alpha\end{pmatrix} = \begin{pmatrix}-\frac{\Delta}{4E}c2\theta + A & \frac{\Delta}{4E}s2\theta + B\\ \frac{\Delta}{4E}s2\theta + B & \frac{\Delta}{4E}c2\theta - A\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\alpha\end{pmatrix}, \tag{4}$$

with

$$\begin{aligned} A =& \frac{1}{\sqrt{2}}(G_F N_e - (G_{\alpha\alpha} - G_{ee})N_d) \\ B =& \sqrt{2}G_{e\alpha}N_d \end{aligned}, \tag{5}$$

where, for simplicity, we have considered only the two-flavor case ($\alpha = \mu$ or τ). E is the neutrino energy, N_e is the electron number density while N_d is the density of d-quarks, i.e. $N_d = N_p + 2N_n$ in terms of the proton and neutron densities (also, $s\theta = \sin\theta$, etc.).

It is of course possible that the ν masses and vacuum mixings are such that the ordinary MSW effect takes place in the absence of leptoquark mediated interactions. This happens if $s2\theta \gtrsim 10^{-2}$ and $\Delta\ s^2 2\theta \simeq 10^{-7.5}$ eV^2, in which case the transition is non-adiabatic, or for $s2\theta \sim 0.8$ and 10^{-8} eV$^2 \lesssim \Delta \lesssim 10^{-4}$ eV^2, which is the large angle adiabatic solution (the adiabatic conversion for $\Delta \simeq 10^{-4}$ eV^2 and $s2\theta \gtrsim 10^{-2}$ is disfavored by Kamiokande results [8]). I want to consider instead the alternative situations discussed in ref. [3-5], in which some of these conditions are not fulfilled but the flavor conversion is still efficient due to the presence of the interaction terms in eq. (2). In particular, I will consider the case in which the neutrinos are massive but their vacuum mixing is negligible and then discuss the situation in which the neutrino masses are negligible. The first possibility could be the consequence of the conservation of the individual lepton numbers by the terms giving rise to the ν masses (e.g. by diagonal λ_6 couplings), conservation that could then be violated by the interaction terms involving leptoquarks; while the second possibility could arise if the mass terms are too suppressed or even absent as a consequence of discrete symmetries.

As it was shown in ref. [3], to have a sufficient reduction of the solar ν_e flux in the absence of vacuum mixing requires that

$$G_{e\alpha}(N_p + 2N_n) \gtrsim \frac{10^{-2}}{2} G_F N_e, \tag{6}$$

and this is satisfied if

$$\lambda_{k11}\lambda_{k\alpha 1} \gtrsim 10^{-3}\left(\frac{m_{\tilde{D}_k}}{100\ \text{GeV}}\right)^2. \tag{7}$$

The strongest experimental constraint in this product of couplings for $\alpha = \mu$ ($\nu_e \to \nu_\mu$ conversion) comes from the upper bound on the branching fraction for the process $\mu \to 3e$, that can proceed through the 1-loop process $\mu \to e\gamma^*$ (the virtual leptoquark running inside the loop), with the consequent decay $\gamma^* \to e^+e^-$. This imposes [7] the bound

$$\lambda_{k11}\lambda_{k21} \lesssim 4\times 10^{-4}\left(\frac{m_{\tilde{D}}}{300\ \text{GeV}}\right)^2. \tag{8}$$

Hence, we see that in this model the $\nu_e \to \nu_\mu$ conversion is not allowed. Instead, for the $\nu_e \to \nu_\tau$ conversion the strongest bound arises from the tree-level decay $\tau^- \to \rho^o e^-$ and the corresponding constraint $\lambda_{k11}\lambda_{k31} \lesssim 2 \times 10^{-2} \left(\frac{m_{\tilde{D}}}{100 \text{ GeV}}\right)^2$ [4] is well compatible with eq. (6). These couplings also induce $n \to pe\nu_\tau$, what gives an incoherent contribution to β-decay processes but leading to less stringent constraints.

The reduction in the ν_e flux here is very similar to the one in the ordinary MSW effect, so that there will be a non-adiabatic conversion if eq. (5) holds and the ν masses satisfy [3]

$$\Delta \left(\frac{G_{e\tau}}{G_F}\right)^2 \simeq 10^{-9}\text{eV}^2, \tag{9}$$

while the large angle adiabatic conversion is not compatible with the bound from $\tau \to \rho e$. Thus, in this scenario we expect also a large reduction in the rate of the Galium detectors. Let us note that improved constraints on the branching $Br(\tau \to \rho e)$ from future τ factories and also ep collisions at HERA (looking for $ep \to \tau X$) may be able to further test the allowed window of solutions.

Turning now to the case in which the masses are negligible ($\Delta \ll 10^{-8}$ eV^2), in order that the neutrinos find a resonance in their way through the matter it is necessary that the effects of the ν_e charged current interactions be compensated now by the leptoquark mediated interactions. Hence, at some point the diagonal entries of the matrix in eq. (4) should become equal, i.e.

$$(G_{\alpha\alpha} - G_{ee})(1 + 2Y_n) = G_F. \tag{10}$$

For solar neutrinos, since the value of $Y_n \equiv N_n/N_e$ is small (~ 0.5 in the center and ~ 0.15 in the surface of the sun [9]), the factor $(1 + 2Y_n)$ changes very little in the ν path. Furthermore, this smooth behaviour makes the resonance broad, leading to a flavor conversion that is largely adiabatic. This leads to too much ν_e conversion unless the peak of the resonance is close to the center or to the surface of the sun, so that there is only partial resonance crossing. Hence, the appropriate reduction of the ν_e flux requires very specific values of the effective couplings [4,5]. (In a supernova, Y_n changes significantly and this mechanism may lead to a resonant behaviour in a thin layer along the ν path.)

As was shown in ref. [5], deep-inelastic ν-q scattering constraints preclude the possibility of achieving the large couplings $G_{\mu\mu}$ or G_{ee} required for the $\nu_e \to \nu_\mu$ conversion in the sun by interactions with d_L quarks. The coupling G_{ee} is further constrained in this model since it would induce an effective V-A type NC coupling of electrons with u-quarks, so that atomic parity violation and polarized eD scattering constrain $|G_{ee}|$ to be below the level of $\sim 10^{-1}G_F$. No strong model-independent bounds apply to the coupling $G_{\tau\tau}$

involved in the $\nu_e \to \nu_\tau$ conversion, but in the E_6 model the strongest effect induced by the leptoquarks mediating the $\nu_\tau d \to \nu_\tau d$ scattering is their contribution to the τ decay channel $\tau^- \to \rho^-\nu,\ \pi^-\nu$. Since the effective coupling for the leptoquark mediated decay needs to be $G_{\tau\tau} \sim G_F/2$ (from eq. (10)), the corresponding branching fractions are affected by more than 50 %, in clear contradiction with their experimental agreement with the SM predictions at the few percent level. Hence, no resonance for massless neutrinos can occur in the sun in this model. An important difference between this model and the broken R parity model is that the exchanged particle is always an isosinglet. The constraint on $G_{\tau\tau}$ from τ-decays does not apply when an isodoublet is exchanged, as was considered in refs. [4,5]. Let us note also that a previous attempt [10] to obtain a resonant behaviour for massless neutrinos in an E_6 model, but where the non-universal neutrino NC interactions were due to the mixing of the ordinary neutrinos with heavy isosinglets, also led to negative results. Hence, these mechanisms may only be of some relevance in stellar objects like neutron stars, where the much smaller relative electron density may be compensated by means of a much weaker FDI of the neutrinos with quarks.

We conclude then that, if the neutrino masses are such that they lead to a resonant behaviour in the propagation of the solar neutrinos, the leptoquark mediated interactions may affect significantly the $\nu_e \to \nu_\tau$ conversion and can lead to a solution to the solar neutrino problem even in the absence of vacuum mixings. Instead, the experimental constraints exclude the possibility that in this model a resonant conversion in the sun takes place for massless neutrinos.

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